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## Electro-optic scanning of light coupled from a corrugated LiNbO<sub>3</sub> waveguide<sup>a)</sup>

C. S. Hong and A. Yariv

California Institute of Technology, Pasadena, California 91125

B. Chen

Hughes Research Laboratories, Malibu, California 90265

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Light diffracted from a grating output coupler in a Ti-diffused LiNbO<sub>3</sub> waveguide is scanned electro-optically. Using a coupling length of 2.5 mm in our arrangement we have demonstrated a scanning capability of one resolved spot per 3 V/μm applied field.

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Periodic perturbations of dielectric waveguides have been used extensively for reflection,<sup>1</sup> coupling,<sup>2</sup> and deflection.<sup>3</sup> In the latter case Bragg diffraction of light from a variable wavelength acoustic wave was used for scanning the light beam.<sup>4,5</sup>

In this paper we report on a method of beam scanning in which the direction of light diffracted from a grating output coupler in a dielectric waveguide is controlled, via the electro-optic effect, by an applied electric field. The principle of the device was demonstrated using a LiNbO<sub>3</sub> waveguide in the manner sketched in Fig. 1. Consider a waveguide mode with a propagation constant along the  $x$ -axis  $\beta$  which is incident on a grating coupler with a period  $\Lambda$ . The wave will be diffracted into air with an angle  $\phi$  with respect to the  $x$  axis. The angle  $\phi$  is determined with the help of the subdiagram in Fig. 1

$$\beta - 2\pi/\Lambda = k \cos \phi, \quad (1)$$

where  $k = 2\pi/\lambda$  and  $\lambda$  is the vacuum wavelength. If we define an effective-mode index  $n_{\text{eff}}$  by  $\beta \equiv kn_{\text{eff}}$ , then Eq. (1) becomes

$$n_{\text{eff}} - \lambda/\Lambda = \cos \phi. \quad (2)$$

For a given  $\lambda$  and  $\Lambda$ , the diffraction angle  $\phi$  depends on the index  $n_{\text{eff}}$ . The angle of deflection corresponding to a small change of index is then

$$\Delta\phi = -\Delta n_{\text{eff}}/\sin \phi. \quad (3)$$

The number of resolvable spots  $N$  in the angle of deflection is obtained by dividing the magnitude of  $\Delta\phi$  by the

angular divergence  $\delta\phi$  of the coupled wave. In a structure with uniform waveguide and grating parameters this angular divergence is diffraction limited by the finite coupling length  $L$

$$\delta\phi = \lambda/(L \sin \phi), \quad (4)$$

where  $L$  is the shorter of the grating length or the  $1/c$  folding distance for the waveguide mode intensity along the grating. Thus from Eqs. (3) and (4)

$$N = |\Delta n_{\text{eff}}| L/\lambda. \quad (5)$$

The number of resolvable spots  $N$  is thus independent of the choice of  $\phi$  or  $\Lambda$ .

To estimate  $\Delta n_{\text{eff}}$ , we chose both the direction of the

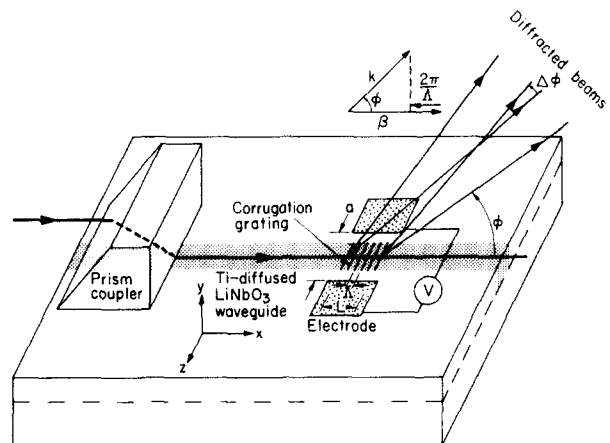


FIG. 1. Schematic diagram of the electro-optic beam scanner.

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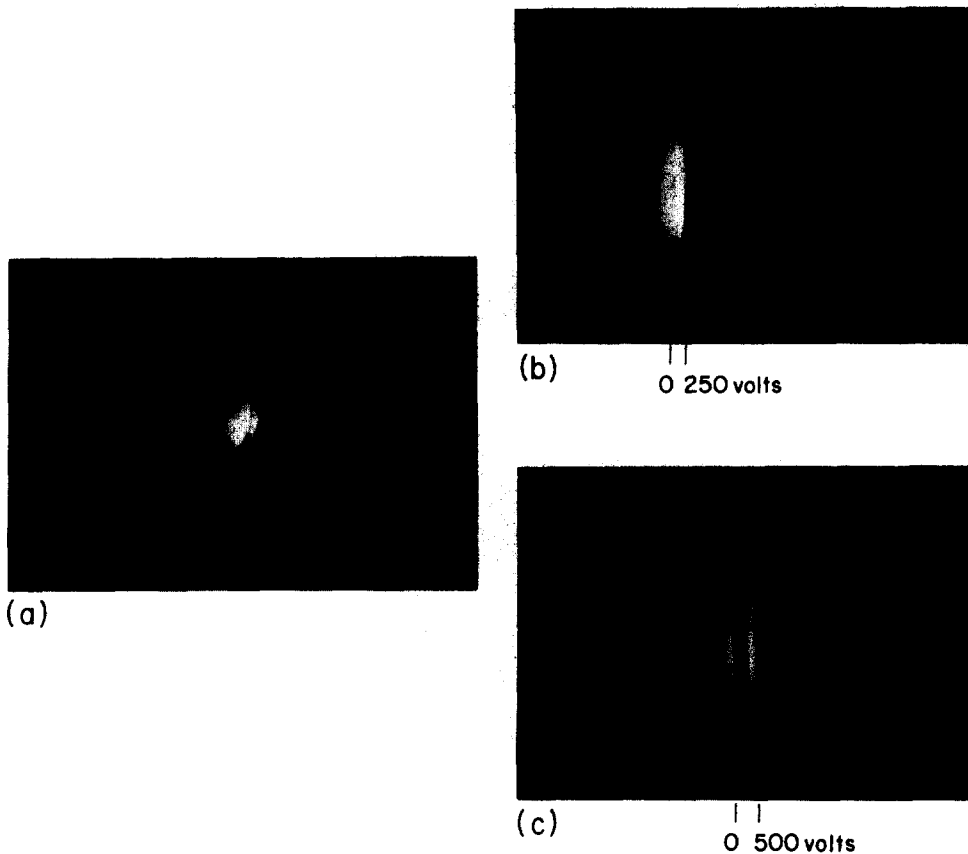


FIG. 2. (a) Typical far-field diffraction pattern of the coupled wave from a planar waveguide. (b) and (c) are photographs of the resolved spots corresponding to the applied voltages as indicated.  $a = 33 \mu\text{m}$ .

applied electric field and that of the mode polarization as parallel to the  $z$  (optic) axis of  $\text{LiNbO}_3$ . The electro-optic index change  $\Delta n_e$  is given by<sup>6</sup>

$$\Delta n_e = -\frac{1}{2}n_e^3 \gamma_{33} E_z. \quad (6)$$

If the waveguide mode is well confined, then we can, to a high degree of accuracy, approximate  $\Delta n_{\text{eff}}$  by  $\Delta n_e$  with  $E_z$  given by<sup>7</sup>

$$E_z = (2/\pi)(V/a), \quad (7)$$

where  $V$  and  $a$  are the applied voltage and separation between the two electrodes, respectively.

In the experiment, both planar and channel Ti-diffused  $\text{LiNbO}_3$  waveguides were used. The grating, which is in the form of a periodic surface corrugation, was fabricated by first recording an interference pattern (derived from a He-Cd laser at  $3250 \text{ \AA}$ ) in the photoresist coating and then developing the photoresist and transferring the pattern to the waveguide surface by ion-beam etching. We chose a shallow corrugation to ensure that the coupling length  $L$  was the geometrical length of the grating. The period and height of the grating rulings were determined using an  $\text{Ar}^+$  laser line at  $4579 \text{ \AA}$ . The  $\text{TE}_0$  mode at  $\lambda = 6328 \text{ \AA}$  was excited in the waveguide by a rutile prism coupler and diffracted out to air by the corrugation grating.

A planar waveguide was formed by diffusing a  $200\text{-\AA}$  Ti metal film into a  $Y$ -cut  $\text{LiNbO}_3$  substrate at  $975^\circ\text{C}$  for 5 h.<sup>8</sup> The resulting waveguide supported a  $\text{TE}_0$  mode with an index  $n_{\text{eff}} = 2.212$ . The corrugation grating with a period  $\Lambda = 5180 \text{ \AA}$  and a length  $L = 2.5 \text{ mm}$  was then fabricated on top of the waveguide. A typical far-field

diffraction pattern for the coupled wave is shown in Fig. 2(a). The angle  $\phi$  was calculated and measured to be  $8^\circ$ . The measured angular divergence was  $\delta\phi \sim 0.15^\circ$ , which was larger than the calculated value  $\delta\phi_{\text{ideal}} = 0.10^\circ$ . A channel waveguide on a  $\text{LiNbO}_3$  substrate was formed by, first, oxidation of a  $4\text{-}\mu\text{m}$  wide and  $200 \text{ \AA}$ -thick Ti film at  $600^\circ\text{C}$  for 4 h, and then diffusion of the resulting oxide at  $950^\circ\text{C}$  for 5 h.<sup>9</sup> It supported a single mode ( $n_{\text{eff}} = 2.210$ ) with a loss constant  $1 \text{ dB/cm}$ . The grating parameters were  $\Lambda = 4200 \text{ \AA}$  and  $L = 2.5 \text{ mm}$ , so  $\phi \sim 45^\circ$  and  $\delta\phi_{\text{ideal}} \sim 0.02^\circ$ . A typical far-field diffraction pattern of the coupled wave from a  $4\text{-}\mu\text{m}$  channel is shown in Fig. 3(a).

The electro-optically induced index change was produced by applying a voltage to a pair of parallel Al electrodes deposited photolithographically on top of the waveguide. In the case of the planar waveguide, the separation between the two electrodes is  $a = 33 \mu\text{m}$ . Figure 2(b), which is a double exposure, shows two states: without an applied voltage and with a voltage of  $250 \text{ V}$  which corresponds to a field of  $5 \text{ V}/\mu\text{m}$  applied. Figure 2(c) corresponds to  $V = 500 \text{ V}$  where three resolved spots can be obtained. The number predicted by Eq. (5) is 6. Figure 3(b) shows the scanning of the beam coupled from a channel waveguide. The voltage of  $150 \text{ V}$  is applied to electrodes with a spacing of  $10 \mu\text{m}$  ( $E_z \sim 10 \text{ V}/\mu\text{m}$ ). The photograph in Fig. 3(c) shows three well-resolved spots corresponding to voltages of 0, 100, and 200, respectively. From the measurement,  $N \approx 5$  when  $V = 200 \text{ V}$ . The theoretical number is 8. The discrepancies between the measured and the calculated values are partly due to an overestimate of  $\Delta n_{\text{eff}}$ , and, partly, to imperfections in the structure.

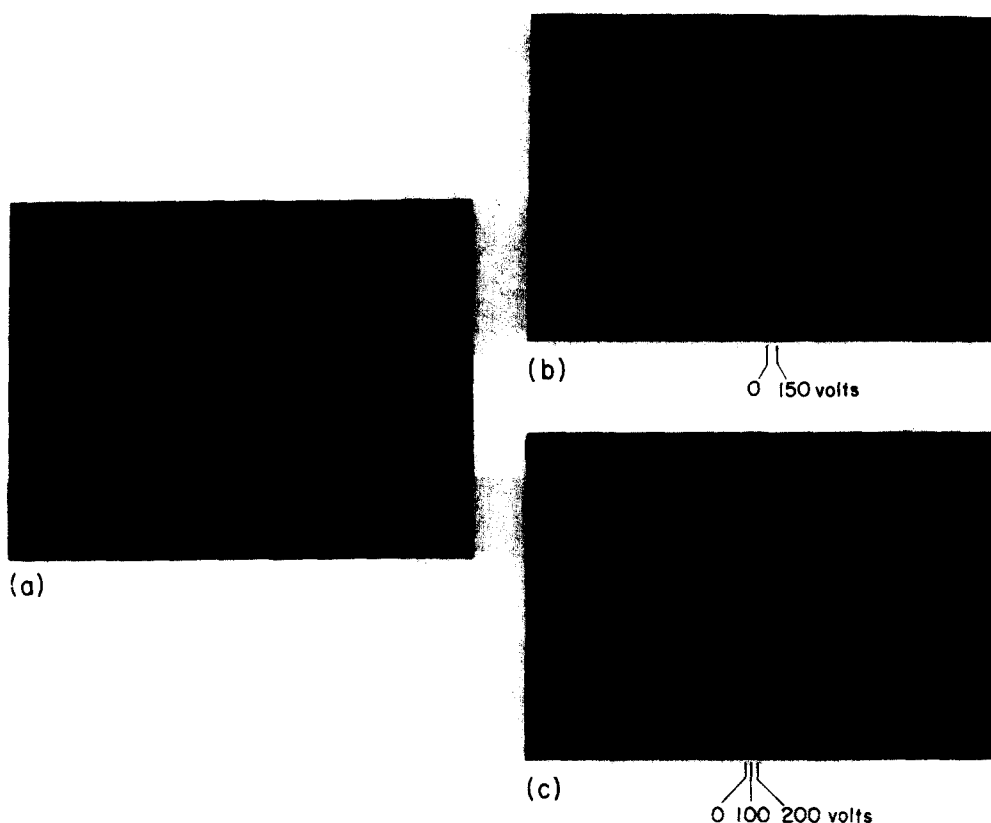


FIG. 3. (a) Typical far-field diffraction pattern of the coupled wave from a 4- $\mu\text{m}$  channel waveguide. (b) and (c) are photographs of the well-resolved spots corresponding to the applied voltages as indicated.  $a = 10 \mu\text{m}$ .

In this application we have used  $\Delta n_e = (1-2) \times 10^{-3}$ . A further reduction of the voltages required can be made by decreasing the separation between the two electrodes. The resolution can be improved by increasing the coupling length in the grating with a corresponding penalty of the switching speed.

In conclusion, we have demonstrated angular scanning of a beam coupled from a corrugated  $\text{LiNbO}_3$  waveguide. This was done by using the electro-optic effect to modulate the index of refraction in the corrugated section of the waveguide. The number of resolution elements can be improved by increasing the coupling length in the grating and is only limited by the dielectric breakdown of the waveguide material. We have demonstrated the scanning capability of one resolved spot per  $3 \text{ V}/\mu\text{m}$  applied field. In principle, by using a grating of  $1 \text{ cm}$  length and an applied field of  $40 \text{ V}/\mu\text{m}$  in Fig. 1, the number of resolution elements should be  $\sim 100$ .

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